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RAPID CHARACTERIZATION OF THE DEGRADATION OF COMPOSITES USING PLATE WAVES DISPERSION DATA

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INTRODUCTION

NDE methods are needed to determine the structure integrity, stiffness and durability (residual life) of structures and they can be extremely useful in assuring the performance of structures using smaller safety factors. While the integrity and stiffness can be extracted directly from NDE measurements, strength and durability can not be associated with physical parameters and therefore, cannot be measured by NDE methods. Specifically, NDE methods are developed to detect and characterize flaws and to determine the material properties of test specimens. For many years, composites as multi-layered anisotropic media, have posed a challenge to the NDE research community. Pulse-echo and through-transmission are the leading methods that are used in practice to evaluate the quality of composites. However, these methods provide limited and mostly qualitative information about the material properties and many defects. Following the discovery of the LLW and the Polar Backscattering phenomena in composites [1, 2], numerous experimental and analytical studies have taken place using obliquely insonified ultrasonic waves [3-5]. These studies led to the development of effective quantitative NDE capabilities to determine the elastic properties, to accurately characterize defects and even to evaluate the quality of adhesively bonded joints [6, 7]. In spite of the progress that was made both theoretically and experimentally, oblique insonification techniques are still academic tools and have not yet become standard industrial test methods for NDE of composite materials. The authors investigated the issues that are hampering the transition of these methods to the practical world of NDE and are involved with extensive studies to address these issues. This paper covers the progress that was made by the investigators in tackling the theoretical and experimental issues to solidify the foundation of the techniques and their transition to practical NDE tools.

LEAKY LAMB WAVE PHENOMENON

The phenomenon leaky Lamb wave (LLW) is induced when a pitch-catch ultrasonic setup is applied to a plate-like solid immersed in fluid as the result of resonant excitation of plate waves that leak waves into the water and interfere with the specular reflection. This phenomenon was discovered in 1982 using Schlieren imaging system while testing a composite laminate [1]. This discovery led to numerous studies of ultrasonic wave propagation in composites and accurate analytical modeling of the wave behavior in composite materials. Towards the end of 1982, Bar-Cohen and Chimenti [1] made an extensive investigation of the characteristics of the LLW phenomenon and its potential for NDE applications. The initial efforts concentrated on experimentally documenting the observed modes and the effects of defects. This effort was followed by numerous studies of the phenomena [see, e.g., 3-5]. In 1987, Bar-Cohen and Mal, developed effective capabilities to accurately model the wave behavior [6] and to invert the elastic properties using the dispersion data. This study was later expanded to NDE of bonded joints [7]. Follow-on studies by these investigators showed that the capability to invert the elastic properties is limited to the matrix dominated ones [8]. To overcome this limitation, which is associated with the need for angles of incidence as small as 8^{o}, a methodology that is based on using ultrasonic pulses was developed for the determination of the material's stiffness constants [9]. Assuming that the material is transversely isotropic and using pulses in pitch-catch and pulse-echo experimental arrangements, it was shown that all the five elastic constants can be determined fairly accurately. A parametric study was conducted and the expected error was determined for the various determined constants in relation to experimental errors. It was also shown that, C_{12}, the constant with the most sensitivity to defects and, while it can be inverted, it is seriously affected by errors in the incident and polar angles.

The experimental procedure that is associated with the leaky Lamb wave phenomenon employs a pitch-catch setup where the impinging wave interacts with the material and the reflection represents the dispersive spectral characteristics of the layered material [Fig. 1]. Evaluation of the minima in the reflection spectra at different angles of incidence provides information about the various wave modes in the form of dispersion curve. The dispersion curves for composite materials and bonded joints were analytical modeled and were very well corroborated experimentally confirming the accuracy of the model.

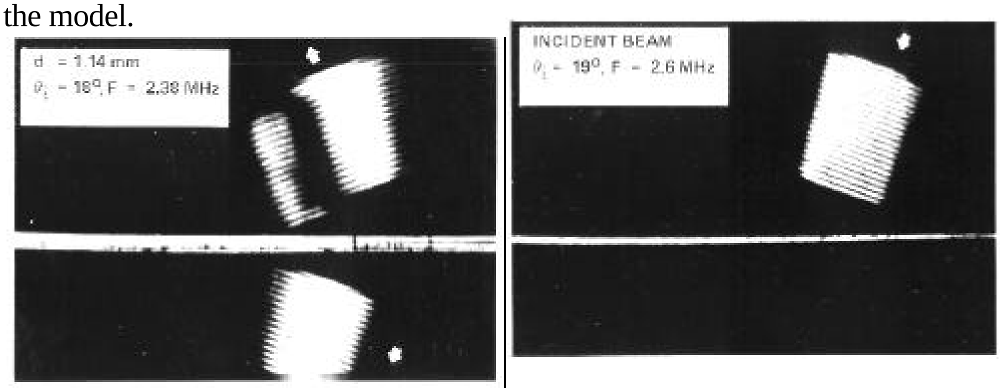


Figure 1: A Schlieren image of the LLW phenomenon showing a tone burst before and after impinging on the graphite/epoxy laminate.

The experimental acquisition of dispersion curves for composite materials requires accurate control of the angle of incidence/reception and the polar angle with the fibers. The need to perform these measurements rapidly and accurately was effectively addressed at JPL where a specially designed LLW scanner was developed. With the aid of a personal computer, the scanner controls the height, angle of incidence and polar angle of the pitch-catch setup. The LLW scanner controls the angle of incidence/reception simultaneously while maintaining a pivot point on the part surface. A view of the LLW scanner installed on a C-scan unit is shown in Figure 2. It allows acquisition of dispersion curves with angles of incidence between 12^{o} and 70^{o}, polar angles in the full 360^{o} range and the height can be varied over a range of 10 cm. A computer code was written to control the incidence and polar angles, the height of the transducers from the sample surface, and the transmitted frequency. In the past, the data acquisition involved the use of sequentially transmitted tone-bursts at single frequencies over a selected frequency range (within the 20dB level of the transducer set). Reflected signals are acquired as a function of the polar and incidence angle and are saved in a file for analysis and comparison with the theoretical predictions. The minima in the acquired reflection spectra represent the LLW modes and are used to prepare the dispersion curves (phase velocity as a function of frequency). The incident angle is changed incrementally within the selected range and the reflection spectra acquired. For graphite/epoxy laminates the modes are identified for each angle of incidence in the range of 12^o to 50^o to allow the use of free-plate theoretical calculations. At each given incidence angle, the minima are identified and are added to the accumulating dispersion curves, and are plotted simultaneously on the computer display (Figure 3). While the data acquisition is in progress, the acquired minima are identified on both the reflection spectra and the dispersion curve.

Figure 2: A view of the LLW scanner (on the right portion of the bridge) installed on the JPL's C-scan system

THEORY AND DATA INVERSION

The locations of the minima in the reflection coefficients are highly sensitive to the thickness and the stiffness constants of the plate and are insensitive to the damping parameters as well as the presence of water in a broad frequency range. Thus the dispersion data can, in principle, be used to determine accurately these properties and any changes in their values during service. The phase velocity of guided waves in a composite laminate in absence of water loading is obtained from the theoretical model as a transcendental equation of the form,

$$G\,(\mathrm{v}, f, c_{ij}, H) = 0 \qquad (1)$$

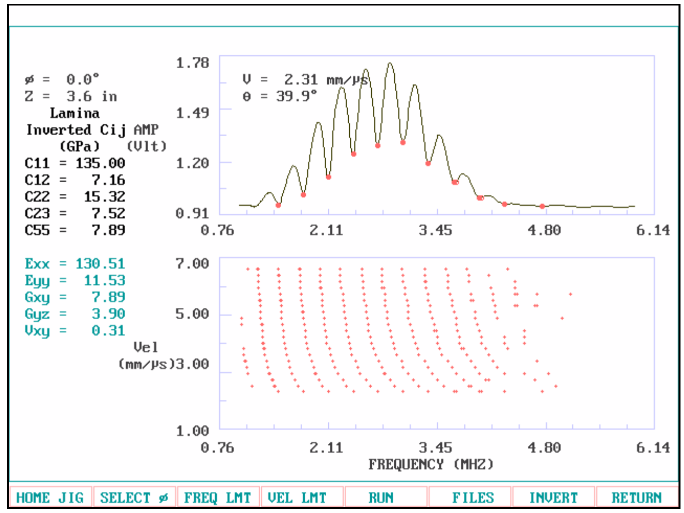
For a given data set $\{f_k, v_k\}$, c_{ij} and H can be determined by minimizing the objective function

$$F\,(c_{ij}, H) = \Sigma\, w_k \left|G_k\right|^2 \qquad (2)$$

where w_k is a suitable weight function and G_k is the value of the dispersion function G at the k-th data set. The minimization can be carried out through a variety of available optimization schemes; we have used the SIMPLEX algorithm to accomplish this.

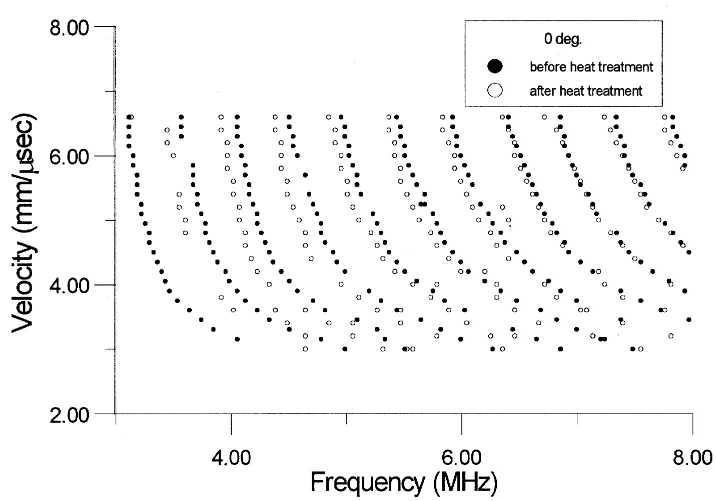
Typical results for a unidirectional graphite/epoxy plate is shown in Figure 3. The material is AS4/3501-6 and the polar angle (i.e., the direction of Lamb wave propagation) is 0^o. The reflected spectrum for 39.9^o incident angle is shown at the top of the figure, and the accumulating dispersion curves are at the bottom. The inverted elastic and stiffness constants are given at the left.

Figure 3: A view of the computer screen with the reflection spectra on the top and the accumulating dispersion curve on the bottom. On the left, the inverted elastic stiffness constants are shown.



To demonstrate the capability of the method to characterize materials degradation of composites, a sample made of AS4/3501-6 $[0]_{24}$ laminate was tested after it was subjected to heat treatment. The sample was exposed to a heat ramp from room temperature to 480^{o} F for 15 minutes, and then was taken out of the oven to cool in open air at room temperature. The sample was tested at a specific location before and after heat treatment. The measured dispersion curves are shown in Figure 4. It can be seen that there are distinct differences in the dispersion data for the specimen before and after heat treatment. Since the heat damage occurs mostly in the matrix, the effect is expected to be more pronounced in the matrix dominated stiffness constants. The constants c_{11}, c_{12}, c_{22}, c_{23} and c_{55} obtained from the inversion process are 127.9, 6.32, 11.85, 6.92 and 7.43 GPa, before heat treatment, and 128.3, 6.35, 10.55, 6.9 and 7.71 GPa, after heat treatment. The most noticeable and significant change is in the stiffness constant c_{22}, which is the property most sensitive to variations in the matrix resulting in a reduction in the transverse Young's modulus.

Figure 4. The measured dispersion curves of a $[0]_{24}$ graphite-epoxy panel before and after heat treatment.



It should be noted that equation (1) is strongly nonlinear in c_{ij} and H, and its solution is non-unique. Thus extreme care must be taken in interpreting the numerical results obtained from the inversion of the dispersion data. On the basis of extensive parametric studies of equation (1) we have concluded that only the thickness and the matrix dominated constants c_{22}, c_{23} and c_{55} can be determined accurately from the inversion of the dispersion data. This is due to the fact that the dispersion function G is not very sensitive to the fiber dominated constants c_{11} and c_{12}. These two constants can be determined accurately from the travel times and amplitudes of the reflected short-pulse signals in the oblique insonification experiment. The composite is modeled as a transversely isotropic and dissipative medium and the calculated dispersion curves are compared to the experimental data using the LLW setup.

LLW EXPERIMENTAL CAPABILITY ENHANCEMENT

To bring the LLW technique to a practical use, the issues that affect its industrial NDE applications have been investigated and they were identified to include:

a) Material density - The inverted material constants assume that the material density is known. NDE measurement of the material density can be done by radiography but this method is not practical and an alternative method of measuring the density is needed.

b) Multi-orientation laminates - The inversion algorithm developed for the determination of the elastic properties has been very successful for unidirectional laminates. The analysis of laminates with multi-orientation layers using ply by ply analysis is complex and leads to ill-posed results. The authors are currently studying methods of inverting the material elastic properties without the necessity to deal with the individual layers.

c) Complex data acquisition - The LLW data acquisition setup is complex and the related process is not user friendly. We have significantly improved the data acquisition process through integration of software and hardware. The computer optimizes the setup height to assure the greatest ratio between the maximum and minimum amplitudes in the reflected spectrum. The polar angle is set using the polar backscattering technique [2] that allows identification of the direction of the first layer. Further, a user friendly control setup that operates on the Widows platform is being written to allow interactive software control.

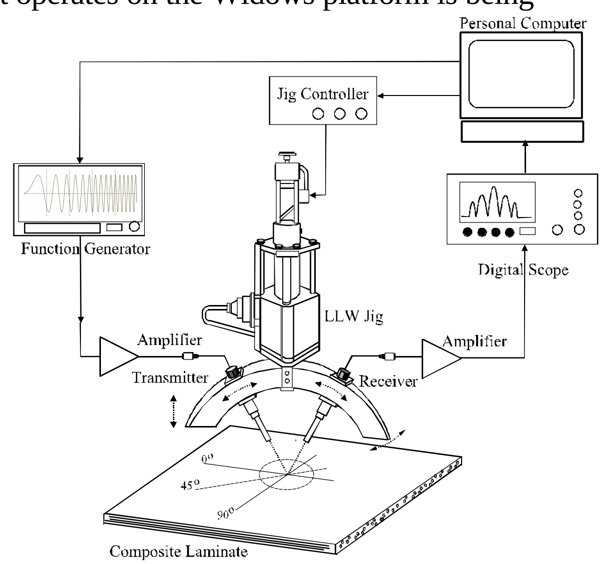


Figure 5: A schematic view of the rapid LLW test system.

d) Time-consuming process - Determination of dispersion curves is time consuming and takes between 10 and 20 minutes for a single point. Recent development by the authors allows the measurement of the dispersion curves at a significantly higher speed than before. The experiment setup is depicted in Figure 5. At selected angles of incident the reflection spectral data is presented in real time directly on the digital scope after being amplified and rectified by an electronic hardware. A function generator induces a frequency sweep in the selected range and is fed to the X-axis of the digital scope whereas the amplitude to the receive signals is fed to the Y-axis. A reference frequency marker is employed to calibrate the acquired spectral data when converting the received signal from time domain to frequency domain. The reflection spectra are acquired in real time while filtering the high frequency noise and providing reliable data at a range of amplitudes that are significantly lower than were used in prior studies. Using this technique, a dispersion curve that is based on a set of 20 angles of incidence along a single polar angle is acquired in about 45 second. This method makes the process of acquiring LLW dispersion curves almost a real time one and is an important step towards making the method a practical quantitative tool for both inversion of the elastic properties and flaw characterization.

CONCULSIONS

Theoretical and experimental studies of the LLW phenomenon have led to a significant progress in understanding the wave behavior in composites. Effective analytical tools were developed for the inversion of data for material property determination and defect characterization. Further, unique experimental tools were developed allow rapid and accurate data acquisition. In spite of this progress, the phenomenon is still not being employed as a standard quantitative NDE method in industry. To pave the path of this method to become a practical tool, the authors have developed a rapid and user-friendly data-acquisition system as well as analytical tools that automatically determine the wave speeds and elastic constants as well as their degradation. This development simplifies the process of characterizing flaws in composites and bonded joints as well as the determination of the material properties and their degradation.

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